A 512 × 512 SPAD Image Sensor with Built-In Gating for Phasor Based Real-Time siFLIM

Arin Can Ulku[1], Claudio Bruschini[1], Xavier Michalet[2], Shimon Weiss[2], Edoardo Charbon[1]

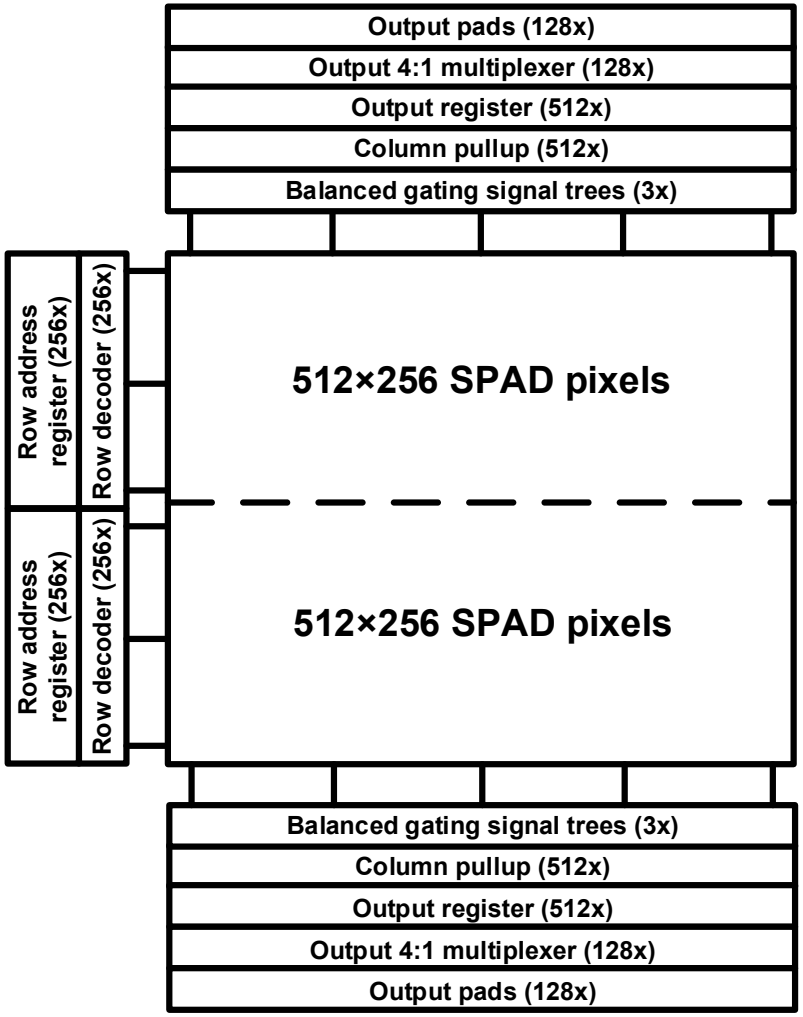
[1]EPFL, Lausanne, Switzerland
[2]UCLA, Los Angeles, CA

Objectives of This Work

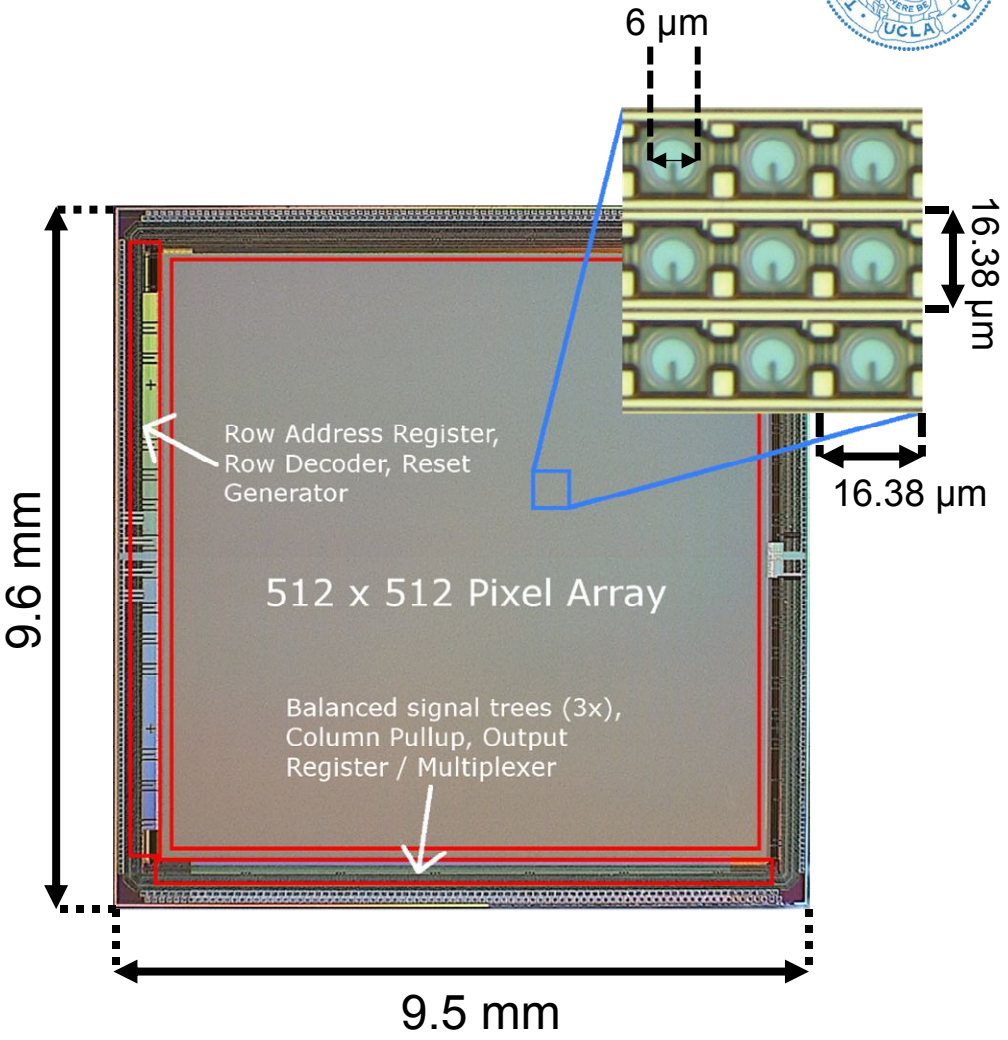
- Time-resolved SPAD image sensor with
  - Large pixel array (512×512)
  - Time gating
    (5 ns min. gate length, 10 ps gate step)
  - High frame rate (195 kfps)
  - Low noise (< 0.1 Hz/μm^2)
  - User friendly

- Target Applications
  - High resolution, widefield FLIM
  - Real time FLIM-FRET analysis
  - siFLIM
  - Localization based super-resolution microscopy
  - 3D time-of-flight imaging

Device Architecture

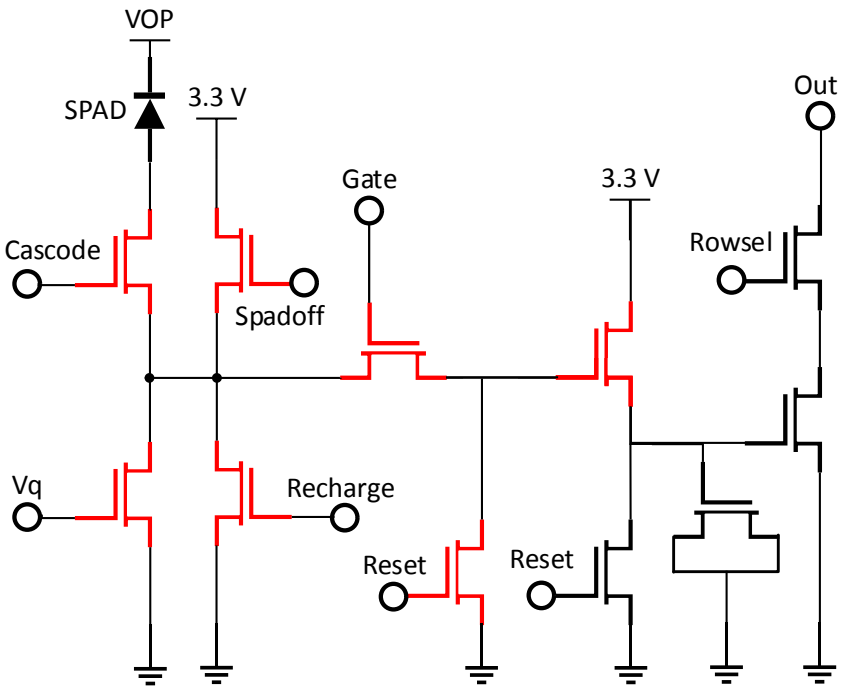


1- Sensor architecture



2- Sensor micrograph

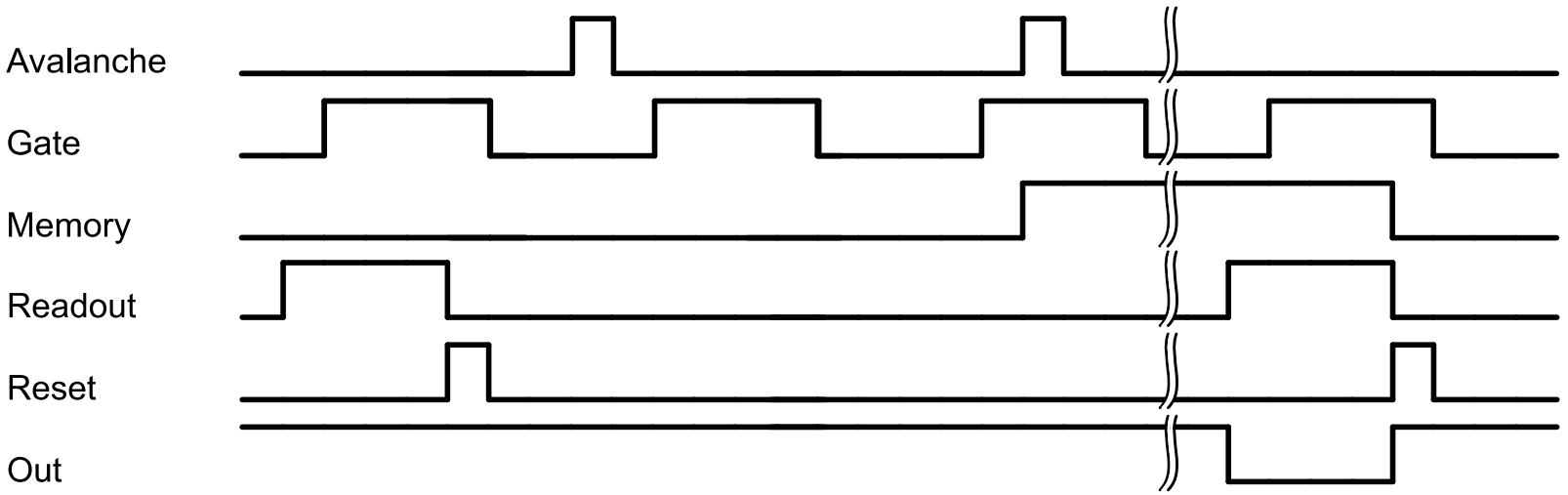
Pixel Architecture



Pixel Features:

- Passive quenching
- Cascode transistor:
  Excess bias up to 6.6 V
  Higher PDP
- Active recharge
- Time gating
- 1-bit DRAM
- Memory reset
- Row selection

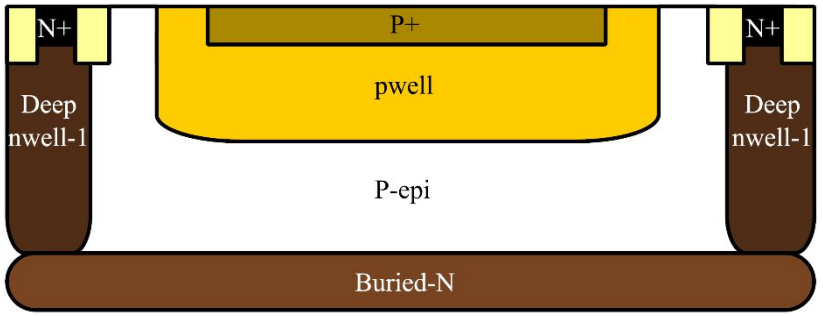
Pixel Operation

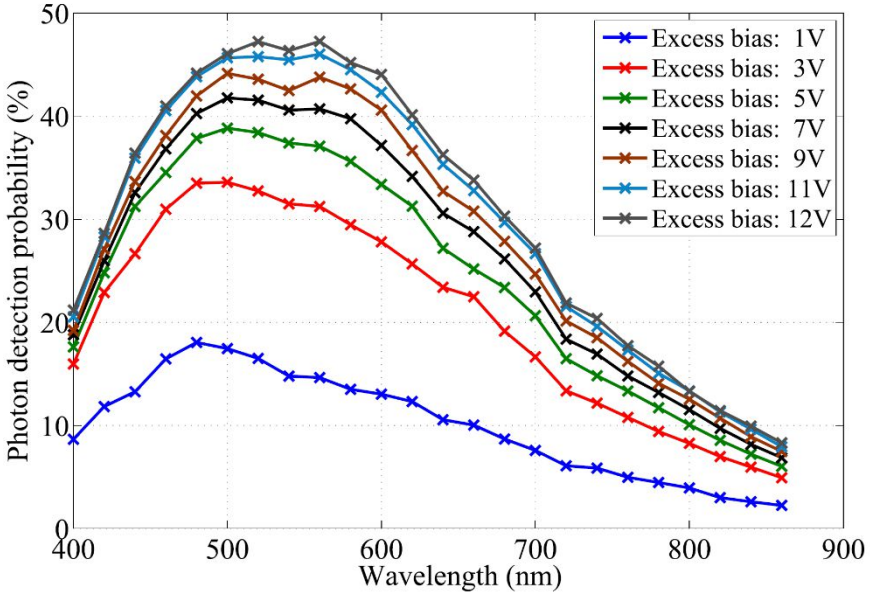


SPAD Characterization

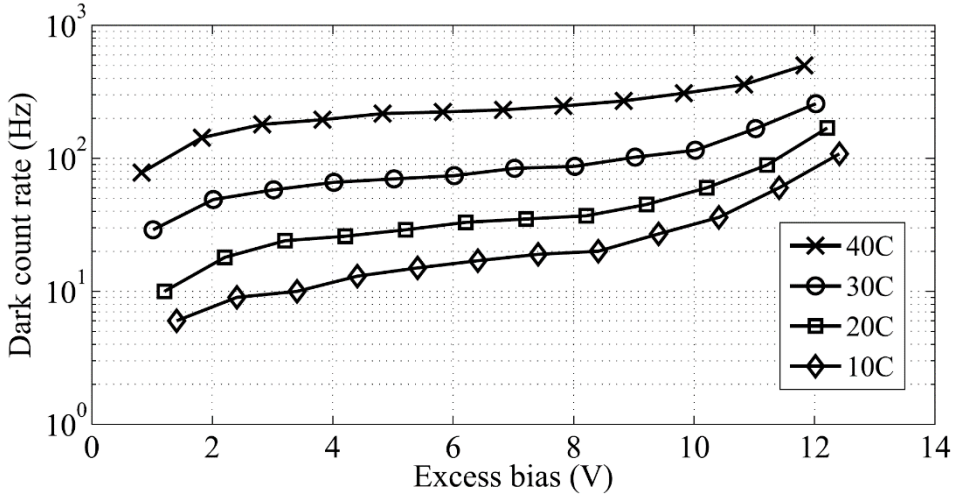
1- SPAD cross section

(Veerappan, IEEE Trans. Electron Devices, 2016)





2- Photon detection probability (PDP)



Active Area: 113.1 μm²

3- Dark count rate (DCR)

Performance Summary

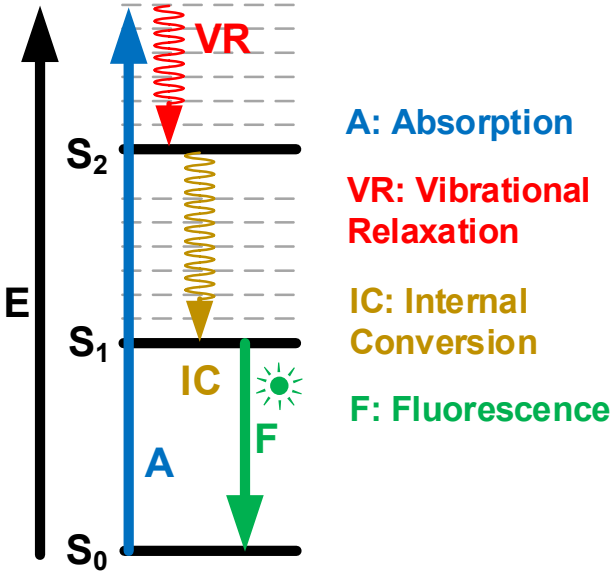
Number of Pixels	512×512
Process	0.18 µm CMOS
Chip Size	9.5×9.6 mm
Pixel Pitch	16.38 µm
Fill Factor	10.5%
Max. Frame Rate (1 bit)	97.7 kfps
Max. PDP	55% (V_{ex} = 11 V, λ = 520 nm)
Dark Count Rate	0.18 Hz/µm^2 (V_{ex} = 3 V) 1.67 Hz/µm^2 (V_{ex} = 11 V)
Gate Jitter	110 ps

Conclusions

	Burri et al.	Dutton et al.	Gasparini et al.	Perenzoni et al.	This Work
Process	0.35 µm	0.13 µm	0.35 µm	0.35 µm	0.18 µm
Array Size	512×128	320×240	100×100	160×120	512×512
Transistors Per Pixel	12	9	7 + 1 METALCAP	8	11
Pixel Pitch	24 µm	8 µm	25 µm	15 µm	16.38 µm
Fill Factor	5%	26.8%	22%	21%	10.5%

- Largest SPAD imager to date (to the best of our knowledge)
- The first array of p-i-n SPADs, which have exceptionally low noise, wide spectrum, and high PDP
- Novel quenching based on cascode transistor for higher-than-technology-allowed excess bias voltage
- The largest continuous frame rate in a SPAD camera to date

Fluorescence Lifetime Imaging Microscopy (FLIM)

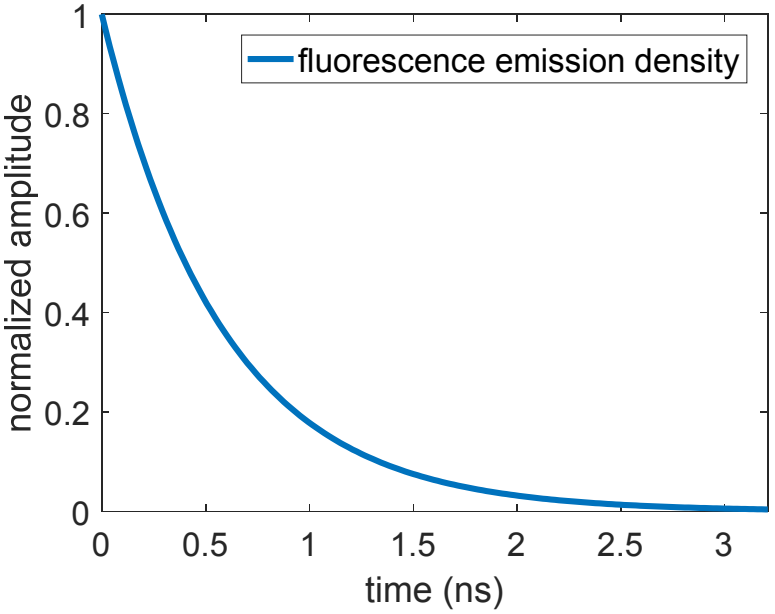


A: Absorption

VR: Vibrational Relaxation

IC: Internal Conversion

F: Fluorescence

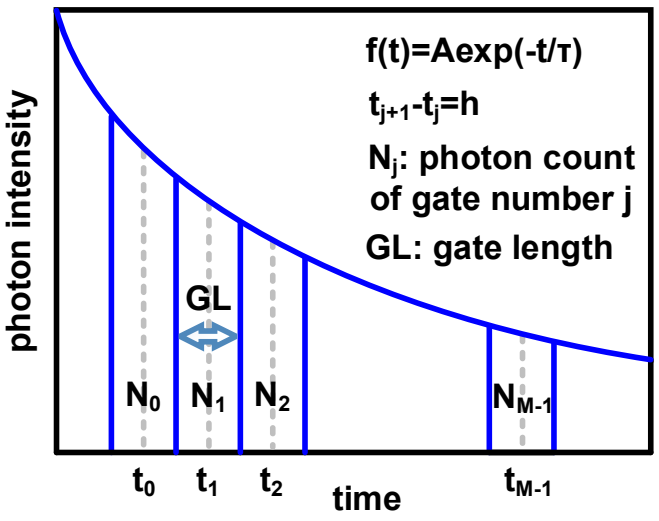


1 - Jablonski diagram showing the electronic states and transitions in a molecule

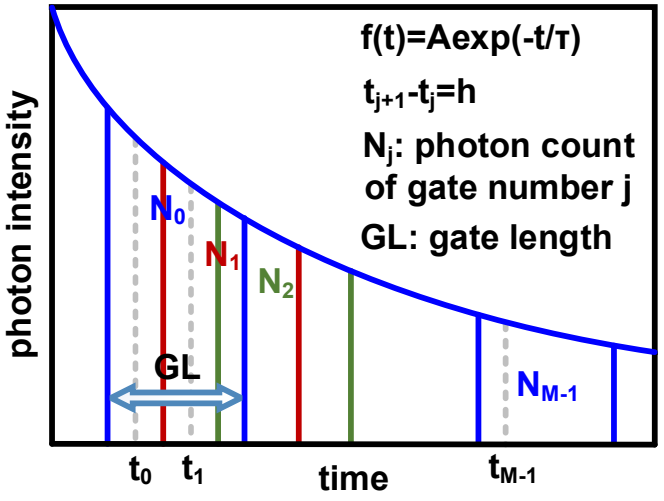
2 - Fluorescence emission decay

Fluorescence lifetime contains a wealth of information regarding e.g. neural activity, metabolism at the sub-cellular level.

Time Gated FLIM



Non-overlapping gates



Overlapping gates

$$g = \cos(2\pi f t_j) \qquad s = \sin(2\pi f t_j)$$

$$g_{avg} = \frac{1}{N}\sum_{i=1}^{N} g_i \qquad s_{avg} = \frac{1}{N}\sum_{i=1}^{N} s_i$$

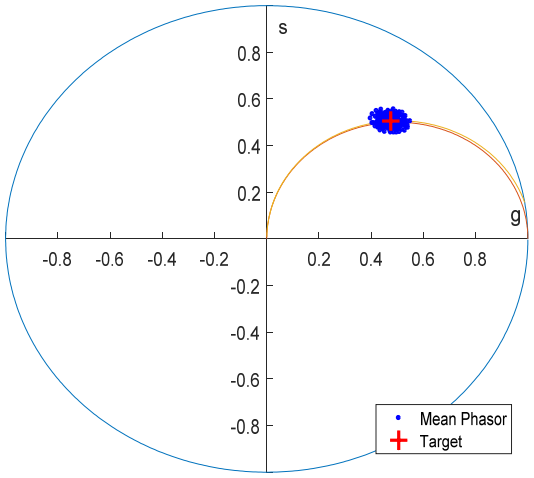
$$g_{avg} = \frac{1}{1+(2\pi f\tau)^2} \qquad s_{avg} = \frac{2\pi f\tau}{1+(2\pi f\tau)^2}$$

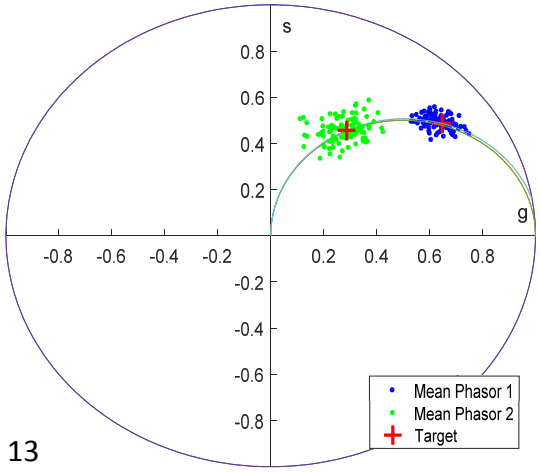
g,s: phasor coordinates

T_j : ToA of the bin number j

N: total photon count

τ: fluorescence decay lifetime





Future Work

- Gate sensitivity test
- Minimum gate length measurement
- Adding microlenses
- Characterization of square SPAD (13% fill factor)
- Implementation of phasor based time gated FLIM
- Demonstrations in target applications
- Investigation of suitability for additional potential applications, such as quanta image sensors (QIS)

Acknowledgements

This work was supported in part by:

- **Swiss National Science Foundation (SNF)**
- **Netherlands Organization for Scientific Research (NWO)**
- **National Institutes of Health (NIH)**

The authors would like to thank:

- **Samuel Burri**
- **Ivan Michel Antolovic**
- **Esteban Venialgo**
- **Scott Lindner**